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Mass number assignments and alpha activities of light polonium isotopes

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With 4 figures in the text

ABSTRACT

Light polonium isotopes have been produced mainly by utilizing heavy ion bombardments. Mass number assignments of these nuclides have been made by use of an electromagnetic isotope separator.

The alpha activities of ^{198}Po, ^{199}Po, ^{200}Po, ^{201}Po, ^{202}Po, ^{203}Po, ^{204}Po, ^{205}Po, ^{206}Po, ^{208}Po and ^{210}Po were studied in this work.

Introduction

In some earlier papers [1–4], the results from alpha-decay studies of light polonium isotopes achieved at the Nobel Institute of Physics have been described. There has also been given a short review of the earlier investigations made by others in this field. Mass number assignments have generally been based on excitation function studies, alpha-decay systematics and genetic relationships. Assignments based on repeated chemical separations of daughter products in this region have been extremely difficult because of the short half-lives involved, the possible existence of fine structure and the lack of definite mass number assignments and knowledge of decay data for the daughter products obtained.

As was pointed out in an earlier paper [3], there was especially a need for final mass number assignments by isotope separations of ^{199}Po and ^{200}Po. The short half-lives and the low alpha-particle intensities available, however, had made such work unfeasible until recently. It is now possible with the isotope separator of our institute [5] to make very rapid separations by use of a special technique [6]. The discharge chamber of the ion source has been provided with two furnaces, one for the stable material necessary to maintain a continuous discharge for the duration of the experiment and one for the radioactive material. This second furnace can be connected to the discharge chamber at a convenient moment when the radioactive nuclides have just been produced and when the running conditions have been stabilized.

The present paper describes mainly the achievement of alpha-particle energy spectra from light polonium isotopes, which have been separated by the method outlined above.

Cyclotron bombardments

In the present experiments the polonium isotopes with masses up to 205 have generally been produced by carbon ion bombardments of platinum in the 225-cm cyclotron at the Nobel Institute of Physics [7]. The bombarding technique has been described in detail elsewhere [3].

Internal beams of $^{12}C^{4+}$ were used. The platinum targets have consisted of circular metallic foils, 8 mm in diameter and about 10 μ thick. The platinum of 99.99 % purity was supplied by Johnson, Matthey & Co., Limited, London.

For the collection of the nuclear reaction products, the recoil technique was used. The catcher foils, made of Tygon or VYNS, with thicknesses of about 1 mg/cm^2, were placed close behind the target foils. Generally, three target foils and three catcher foils were used in each bombardment. Within about half a minute after the end of the irradiations the probe could be withdrawn through an air lock and the target holder detached.

The intensities of the carbon ion beams reaching the target holder with energies of 90–130 MeV were in the range $10^{-2} - 10^{-1}$ μA. The bombardments lasted from about thirty minutes to some hours.

In a few experiments polonium isotopes were also produced by neon ion bombardments of wolfram [2].

In studying convenient isotope separation conditions samples of the isotopes ^{206}Po, ^{208}Po and ^{210}Po were utilized. Of these nuclides, the two first-mentioned were obtained by proton bombardments of bismuth in the synchrocyclotron of the Gustaf Werner Institute for Nuclear Chemistry in Uppsala. The proton energy used was about 50 MeV. The bombardments lasted for some hours and the beam intensities were about 1 μA.

Chemical procedures

Chemical separation of ^{210}Po

The samples of ^{210}Po used in the present experiments were obtained from small glass tubes, which had been filled with radon and used in therapy at the Institute of Radiophysics in Stockholm. As is well-known, ^{222}Rn decays to ^{210}Po, which is found in the deposit on the walls of such tubes. After about three years the ^{210}Po activity has reached its equilibrium.

The active deposit was extracted from the radon bulbs by the method of Bjerge [8]. The ^{210}Po samples were then made by electrochemical replacement onto silver foils in 0.4 *M* nitric acid [9].

Chemical separations of ^{206}Po and ^{208}Po

Most often polonium has earlier been separated from bismuth targets by coprecipitation on a carrier compound of, for instance, lead tellurate. Also the electrodeposition of polonium in hydrofluoric acid has been recommended [10, 11]. In the present case the following method, which was shown to be quite satisfactory, was used.

About 1 g of the proton bombarded bismuth target was dissolved in 20 ml of boiling 6 *M* nitric acid. The solution was evaporated to dryness and the nitrate residue dissolved in concentrated hydrochloric acid. The nitrate was converted to chloride by repeated evaporations with hydrochloric acid. The final solution of about 25 ml was made 6 *M* in hydrochloric acid. Hydrazine hydrochloride was added to saturation and the polonium spontaneously deposited onto a silver foil with stirring for some hours.

Some trials were also made using lower acidities for the deposition. They were, however, less successful, as the polonium yields were lower and a black deposit became visible on the silver foils.

Chemical separations of ^{198}Po–^{205}Po

In these cases, chemical separations and isotope separations were most often made from separate samples. The reason was the shortage of time available for the detection of the short-lived activities.

Even if the results from the chemical separation of polonium after carbon ion bombardments of platinum were well-known from earlier experiments done at this institute [3], it was considered to be of importance to check that the conditions for the production of the nuclides were completely reproducible.

Concerning the procedures of the chemical separations used in this case we refer to the earlier papers [2, 3, 11]. The evaporation of polonium at relatively low temperatures has also been used for its purification in the present work [11, 12].

Preparation of organic catcher foils

Organic foils of Tygon and VYNS have similar properties. The foils made of VYNS, a copolymer of polyvinyl chloride and polyvinyl acetate [13], were prepared in the following way.

A solution of about 6 g of VYNS in 100 ml of cyclohexanone was used. The dissolution can be hastened by warming. A calculated amount of this solution was poured onto a water surface in a tray. The spreading of the the liquid was first hindered by a glass rod touching the water surface and the edges of the vessel. The rod was then moved over the surface with a constant speed and the cyclohexanone was left to evaporate. After about five minutes aluminium rings were placed on the VYNS film now formed. The rings, which had been washed with acetone, became attached to the film. After a time they were cut out from the surrounding surface film. They were of the size suited for the target holder arrangement. Other methods to detach the films from the water surface before the preparation have also been used, as, for instance, removal by metallic wire frames or by clean or by specially prepared glass plates.

Electromagnetic isotope separation

The principles of the rapid isotope separation method used in this work were published in 1958 by Uhler and Alväger [6]. The method has been applied to mass number assignments of, for instance, light astatine isotopes in connection with the study of the alpha-radioactive decay of these nuclides [14]. In the studies mentioned, the general procedure, used also in the present investigation, has been presented in more detail.

The most important feature of this separation method is the design of the ion source, which has been equipped with two furnaces. One of them, containing a few milligrams of a carrier with a convenient atomic weight, gives the vapour pressure required for the discharge. The carrier, used also as a mass standard, must be a component of a compound with suitable properties concerning the discharge conditions. The second furnace, which contains the radioactive sample, can be connected to the discharge chamber during the separation at the moment when the activity is just produced and the separator has reached stable running conditions. The second furnace can rapidly be heated up to about 1000°C. A good isotope separation can in this way be made in about ten minutes.

In the present case the ion current was of the order of 10 μA. The resolving power used was about 1000. As carrier and standard mass sources, chlorides of lead, thallium and mercury were used.

Experimental development

The first experiments done with the isotope separator to obtain single polonium isotopes were carried out on the samples containing the relatively long-lived nuclides ^{206}Po and ^{208}Po. In these cases the polonium had been spontaneously deposited on silver foils as described above. The results from the isotope separations were quite satisfactory and the samples obtained in the aluminium collector foils were found to be well suited for alpha-decay studies.

When rapid separations had to be made with the short-lived products obtained from bombardments of thick targets of platinum by carbon ions or of wolfram by neon ions, the dissolution of the targets and the isolation of the polonium was generally too time-consuming. The alpha activity left after both chemical and isotope separations was then often too low for successful measurements, despite the fact that total separation yields could be as high as 10 %.

For the low mass numbers studied after heavy ion bombardments the polonium had to be electrodeposited on platinum foils, which, unlike the silver foils, were able to stand the solutions necessary for the dissolution of the targets [11]. However, in this case polonium left the platinum foil too early in the active material furnace for the attainment of satisfactory separations.

From these preliminary experiments it was found that under the prevalent conditions only the recoil collection technique could be used for obtaining satisfying results. If so, however, the reaction yields from the neon ion bombardments were generally too low for our purposes. Thus with the heavy ion beam intensities available at our institute to date, the carbon beams seem to be the most useful for work of the kind under consideration.

The best solution of the problem of achieving samples sufficiently strong for isotope separation of heavy-ion produced, short-lived activities was to place organic catcher foils directly in the radioactive material furnace of the separator. When the temperature of the furnace became sufficiently high, the organic foils decomposed and the nuclear reaction products enclosed in them were liberated. As polonium is easily vaporized, the yield could be expected to be fairly high by using this simple procedure.

One drawback with the procedure was that the thermal decomposition of the foils increased the pressure in the ion source, which changed the discharge for a short period and caused instabilities in the focusing of the ion beam. By careful heating of the oven, however, it was usually possible to obtain stable conditions again before the collection of the activity started.

When the catcher foils were used, chemical separations were made on separate samples from the same bombardments. For the identification of the components, the different alpha activities obtained after the chemical separation had to be compared with the corresponding activities obtained in the aluminium collector foils after isotope separation. In particular the relative intensities of the peaks in the alpha-particle energy spectra had to be compared in the two cases for different isotopes so that possible contaminations from other elements in the isotope-separated samples could be revealed. The applicability of the rules of alpha systematics, however, generally made this task fairly easy.

Counting technique

The alpha-decay properties of the various polonium isotopes considered in this work were studied by means of an ionization chamber and two multi-channel pulse-height analyzers constructed at our institute [15].

The mechanical registers of one of the pulse-height analyzers had extra contacts, used to activate a channel recorder, which recorded each alpha count obtained with respect to channel number and time of occurrence. From these data the alpha-particle energy spectra and the decay curves could be calculated and drawn. The procedure has been demonstrated in an earlier paper, where astatine studies have been reported [14].

As standard samples for the alpha-particle energy calibrations the following samples have been used:

^{243}Am	(5.266 and 5.224 MeV),
^{241}Am	(5.477 and 5.435 MeV),
^{244}Cm	(5.801 and 5.759 MeV),
^{252}Cf	(6.112 and 6.069 MeV).

In the energy range studied, the background in the ion chamber measurements was less than one count per channel per ten hours.

Results and discussion

It has been suggested that fine structure should be rare in the alpha decays of light polonium isotopes. For even-even alpha emitters this had partly to do with the fact that the energy level spacings above the ground states become progressively greater and the abundances of the alpha groups populating these states progressively lower among the heavy region alpha emitters when lower elements or lower neutron numbers of a particular element are considered [16, 17]. However, the energy level spacing for the first excited state was earlier proposed to reach a maximum already at the 126th neutron shell. By the study of alpha-energy spectra of the even-even alpha emitters these problems have been examined [18, 19].

The mass number assignments for polonium isotopes with low neutron numbers have earlier mainly been based on the investigations of Karraker, Ghiorso and Templeton [20] and of Rosenblum and Tyrén [21]. The last-mentioned authors found a polonium alpha activity of 5.77 MeV, which had not been reported by the first group. This caused some disagreement in the mass number assignments. The activity of 5.77 MeV has been confirmed at our institute [3, 4].

The half-lives of the alpha activities found by Rosenblum and Tyrén in their alpha spectroscopy work [21] were reported as different from each other. For this reason it seemed rather unlikely that some of the entirely resolved alpha peaks in their energy spectra could have been due to fine structure in the decays [4]. They based their

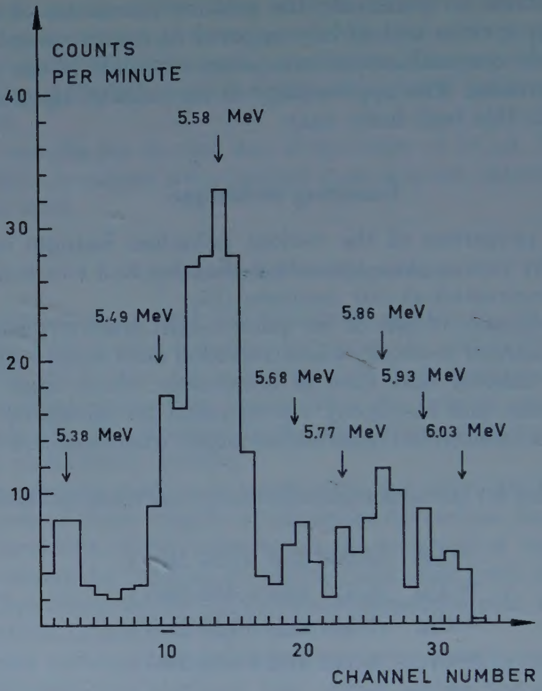

Fig. 1. Alpha-particle energy spectrum of chemically separated polonium activities taken 11–14 minutes after the end of a carbon ion bombardment of platinum.

mass assignments on considerations of alpha systematics, but also stated that their suggestions could not be characterized as definitive [21]. This opinion has also been the common one, reflected in the recent tables of nuclides [22].

The results obtained in the earlier polonium work at this institute [3, 4] generally seem to be valid also concerning the mass number proposals of the activities. However, the results obtained in the present investigation have shown that fine structure occurs among the neutron-deficient polonium isotopes. For comparison between the chemically separated samples and the isotope separated ones, the results shown in Figs. 1, 2 and 3 can be used.

In Fig. 1, an alpha-particle energy spectrum is seen, which was obtained after a rapid polonium separation of the products from the nuclear reaction Pt(^{12}C, xn)Po, where x is the number of neutrons evaporated from the compound nucleus. In this case the bombardment time was 75 minutes. No isotope separation was made. The ion chamber measurements were started eleven minutes after the end of the bombardment and the spectrum was taken during a three minute period. The channel widths were chosen so large that almost the whole spectrum could be obtained on the same recorder paper.

The decay data presented below are generally those which have been obtained after isotope separation. The measurements of the long-lived polonium isotopes with the masses 206, 208 and 210 have also been included in the detailed discussion below, because of the fact that they have earlier not been studied in this way, even if there have been no doubts about the mass number assignments. It was also of some value to compare the results obtained under somewhat different isotope separation conditions.

For the polonium isotopes of masses lower than 206, the activities obtained in the single experiments were very weak. Thus, the statistical basis for the decay data was poor. We think, however, that the results were in most cases sufficient for the identification of the main activities.

The data obtained from the different alpha measurements have been treated in the following way. The number of counts obtained in the single channels of the pulse-height analyzer were plotted against the mean energy values of the channels, estimated to the nearest 5 keV. The results from several experiments were added and the total number of alpha counts were plotted into energy intervals of 0.020 MeV. Those counts, which were on the border-lines between these energy intervals have been divided equally between adjacent units. The method is not quite unassailable as, for instance, single counts may get somewhat different representation in the diagram depending upon their estimated energy values.

A plotting method, for instance, similar to that suggested by Slätis, Hjalmar and Carlsson [23] should strictly be preferred. In our case, however, instead of triangles, unit area isosceles trapezoids with different heights and parallel side lengths, depending upon the different channel widths used, would have represented the probability curves for the energy values of the single alpha counts. The summarized area of all these small unit areas in the diagram would have given the final spectrum. However, the improvement of the diagram would be small compared to the increase in calculation work necessary. For that reason the simple method mentioned above has been preferred in the present paper. Of course, also some other simple alternative methods can be suggested but this will not be discussed here, as the problem in the present case is of minor importance.

The results from the ionization chamber measurements are based on about twenty bombardments with subsequent separations. A detailed discussion is given below for each single isotope.

The nuclides $^{<199}$*Po*

An alpha-activity, probably due to ^{197}Po, has earlier been found from carbon ion bombardments of platinum [3]. The short half-life of about 4 minutes and the relatively low reaction yields obtainable have hitherto made all efforts to find any activity left in the mass 197 position after isotope separation unsuccessful.

In two experiments a few alpha counts were recorded from the samples of mass 198. From those it was impossible to decide, however, whether they were due to a 5.93 MeV activity [3], or to possible contamination from the 199 position.

The isotopes with the masses 196–199 have all been classified by the code symbol C in the 1958 Berkeley table of nuclides [22], which means that the element has been considered as probable and the mass numbers as certain or probable.

The nuclide ^{199}*Po*

In two experiments, relatively many counts were registered close to the energy 5.87 MeV as shown in Fig. 2. A half-life of 13 ± 3 minutes was found from the decay curve obtained. These data were in agreement with those earlier reported from our

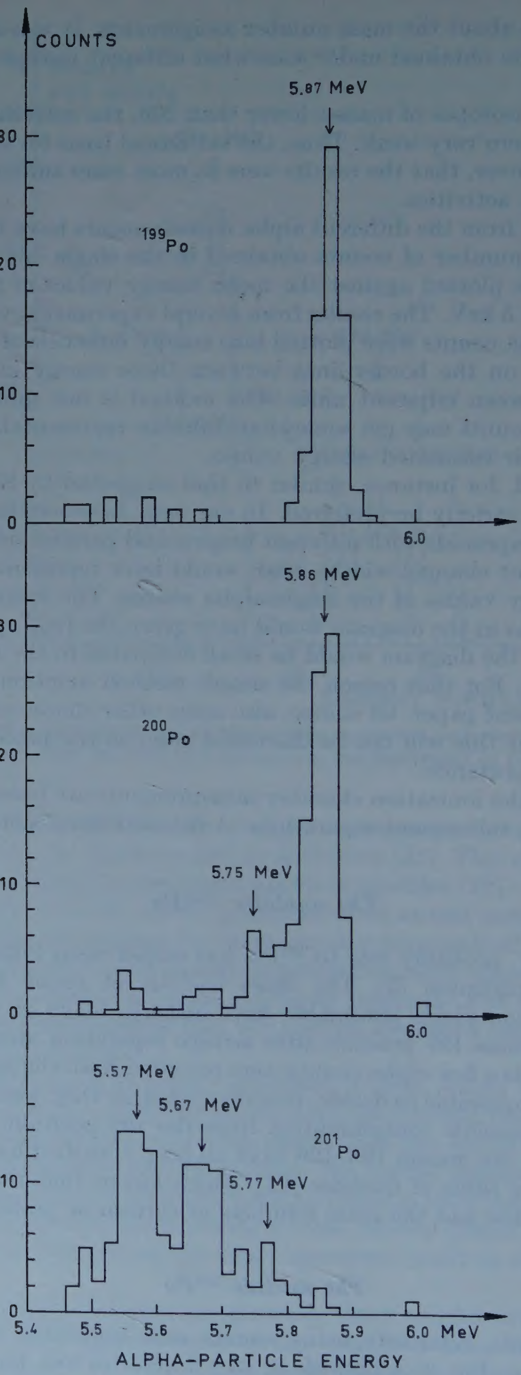

Fig. 2. Alpha-particle energy spectra from isotope-separated samples of ^{199}Po, ^{200}Po and ^{201}Po.

institute [3]. The positive results were achieved in those two experiments in which the yields of all the polonium isotopes were the highest.

For some reason, however, the results were difficult to reproduce for the mass number 199. As the measurements on ^{200}Po gave very similar energy and half-life data, it could not be quite excluded that at least part of the activity might be ascribed to impurities from the mass 200 position due to, for instance, short focusing instabilities during the critical time of the isotope separations. Other data, however, seem to contradict the idea that ^{200}Po was the main source of the activity. Thus, the possible maximum contaminations of ^{202}Po in the 201 position, and of ^{201}Po in the 200 position are relatively low in the same runs. Unfortunately, the evidences for the mass 199 activity must still be considered as somewhat inconclusive. From the results of these measurements the activity could perhaps be characterized with the words "element certain and mass number probable". In similar cases [14] the daughter products obtained in the decays studied have given good support for the mass number assignments. However, in this case, the low alpha activity around 5.5 MeV could hardly be considered as being due to ^{199}Bi.

The nuclide ^{200}Po

This isotope has been classified by the code symbol D in the Strominger, Hollander and Seaborg table of nuclides [22], which means that the mass number has been regarded as not well established. The energy spectrum for the alpha particles emitted from ^{200}Po, shown in Fig. 2, was composed of data from seven different experiments. The peak energy value of 5.86 MeV was 0.01 MeV higher than the mean value obtained from all the experiments. This was due to the fact that the highest alpha-particle intensity was measured in an experiment, where also the highest energy value was obtained after comparison with the standard activities. The half-life determination made from just this experiment gave a value of 12 ± 4 minutes. As only 45 alpha counts were used in this half-life determination, it is quite obvious that the accuracy of such a value must be low compared with those of earlier experiments when no isotope separation was made. On the other hand, however, the overlapping of the activities from two or more mass numbers have made some of the earlier measurements very uncertain.

It is now obvious that the mass assignment of Karraker, Ghiorso and Templeton, [20] for ^{200}Po was right. When Fig. 1 of their paper is examined, a small alpha peak around 5.77 MeV can be seen, which seems to have been neglected by them. This peak was probably the alpha-intensity maximum, which has later been considered as due to ^{200}Po [4, 3, 21]. As shown in Fig. 2 of the present paper, at least part of this "hump" can be explained as a fine-structure component in the ^{200}Po alpha decay. Unfortunately, the number of recorded counts is very low.

The few counts registered at still lower energies in the spectrum of mass 200 were probably due to contaminations from ^{201}Po. This could possibly have been suggested also for the weak 5.75 MeV activity if its half-life had not been known to be around 10 minutes from other experiments [3, 4, 21].

The nuclide ^{201}Po

According to earlier studies [3, 4, 20, 21] ^{201}Po should be expected to have an alpha activity with the particle energy close to 5.68 MeV. This was also shown to be the fact, as seen from Fig. 2. However, from five separate experiments this isotope can be supposed to have a fine structure, which had not earlier been revealed. The reason for this is obviously that the other two intensity maxima found in the alpha spectrum coincide with the maxima from neighbouring mass numbers.

Probably a small fraction of the 5.57 MeV alpha activity was due to impurities from ^{202}Po in two of the five different experiments, which were added for the construction of the diagram in Fig. 2. For this reason the true relative intensities of the peaks would certainly be somewhat changed in favour of the 5.67 MeV activity compared with what is the case in the diagram.

That most of the 5.57 MeV activity discussed here actually was due to ^{201}Po and not to contamination from ^{202}Po was shown by the fact that the half-life of this peak in all the experiments was found to be less than 25 minutes.

The third component had an energy of 5.77 MeV. The half-life determined from the total activity of the best experiments was in this case 16 ± 3 minutes.

It was somewhat astonishing that the 5.77 MeV activity of ^{201}Po, together with the 5.75 MeV activity of ^{200}Po, has given such a low total half-life as about 10 minutes, as had earlier been found. Thus, it could not be excluded that there is a further source of activity, which can contribute to the intensity maximum around 5.77 MeV.

The nuclide ^{202}Po

In the carbon ion bombardments of platinum, under the conditions described above, the most intense alpha activity was due to ^{202}Po. The mass number assignment has in this case earlier been generally accepted. However, ^{202}Po, like ^{201}Po and ^{203}Po, has had a classification code letter B in recent tables of nuclides [22]. This means that the mass numbers have not been considered as certain by the authors of the tables.

The sum of the alpha-particle energy spectra from the mass 202 position studied in five experiments is shown in Fig. 3. The energy maximum at about 5.57 MeV is quite unambiguous. The half-life found was 50 ± 10 minutes, which was accurate enough for an identification. In earlier studies at this institute [3] the half-life from alpha measurements was found to be less than that reported by other investigators [20, 21]. This fact was also found by Harris [24]. From the isotope separated samples no interference from ^{201}Po is expected. Thus, it seems reasonable that the half-life in this case should have been somewhat longer than in those cases, where only chemical separations have been made. However, the difference in half-lives between the isotopes with masses 201 and 202 should have made the decay curve in, for instance, Fig. 3 of reference 3 non-linear, if the intensity of the ^{201}Po alpha activity had been comparable with that of ^{202}Po. For that reason the half-life of mass 202 cannot be much longer than that earlier reported by us, i. e. 43 minutes.

^{202}Po has also been identified as a daughter product of ^{202}At in isotope-separated astatine fractions [14].

The nuclide ^{203}Po

As could have been expected from our earlier studies [3], the alpha activity from this nuclide has been very difficult to detect after isotope separation because of the low alpha branching ratio of the decay. In a few attempts only two alpha counts were recorded, one of which came at the expected particle energy 5.48 MeV. More tedious experiments would probably have given better results. Such efforts were, however,

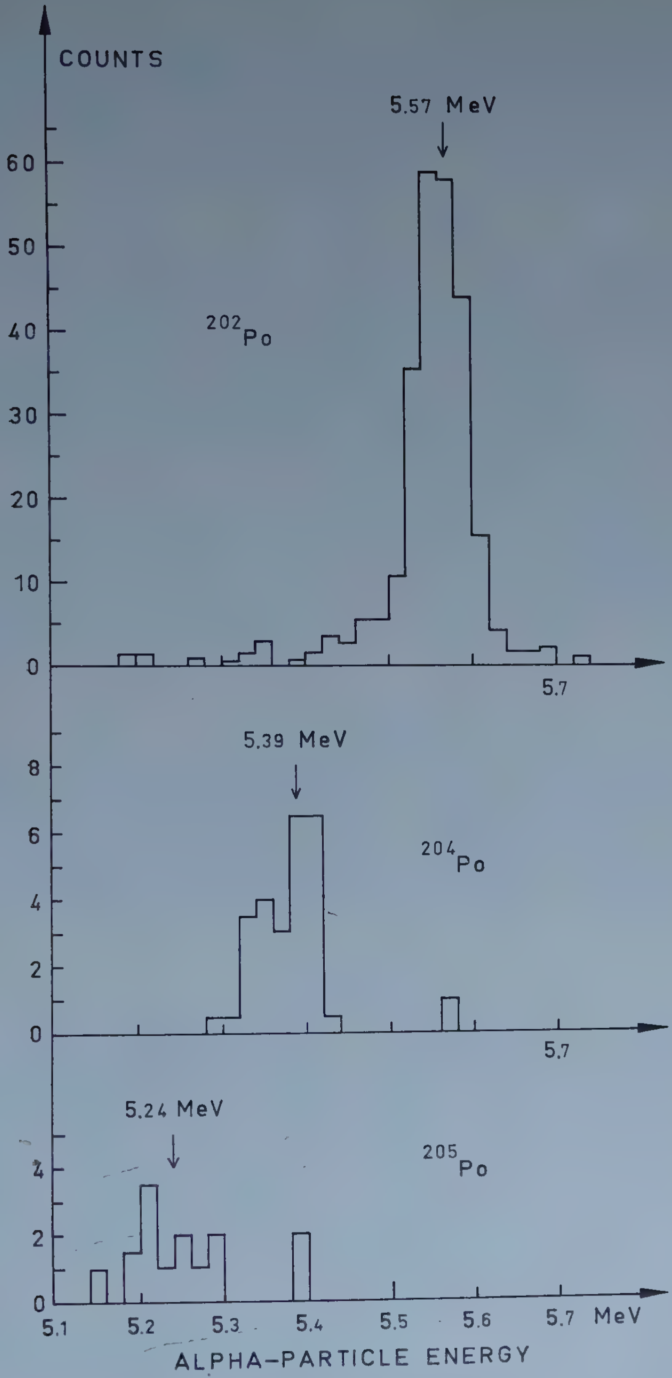

Fig. 3. Alpha-particle energy spectra from isotope-separated samples of ^{202}Po, ^{204}Po and ^{205}Po.

not considered to be worth while since the yield of this isotope was obviously higher in the experiments made by us for studying the astatine isotopes of low masses [14]. As may be seen in Fig. 6 of that paper, an alpha intensity maximum was found at 5.48 MeV for the mass number 203. ^{203}Po had in that case mainly been formed by electron-capture decay of the nuclide ^{203}At, which had been obtained in a high yield under the bombarding conditions used in that investigation.

The nuclide ^{204}Po

This polonium isotope is the one with the lowest mass number, which has hitherto been classified with the code symbol A in the table of nuclides [22].

The energy spectrum obtained for this mass number is shown in Fig. 3. The intensity maximum around 5.39 MeV is the one earlier known for this isotope. The half-life determination was poor in this case as the number of studied decaying atoms was low. By use of the method of plotting the logarithm of the number of remaining counts against time, a half-life of about 4 hours was found. In a chemically separated sample the value 3.6 ± 0.2 hours was obtained.

In the measurements on chemically separated samples, an indication of an alpha activity around 5.32 MeV has been found [3]. From the energy spectrum shown in Fig. 3, one is inclined to think that this activity is also due to ^{204}Po. However, from the four individual spectra of which the one in the diagram has been constructed, it was found that only one intensity maximum could be reproduced. The shape of the peak, in this study, was due to the fact that the energy determinations were somewhat diverging.

The nuclide ^{205}Po

Also ^{205}Po was formed in poor yield for the alpha-decay studies under the experimental conditions used. Thus, from one experiment, the alpha-particle energy spectrum shown in Fig. 3 was obtained in a measurement of several hours. The alpha-particle energy was about 5.24 MeV. Whether fine structure occurs or not was impossible to state from this experiment. The shapes of the intensity curves earlier obtained in the energy spectra of ^{205}Po seemed to suggest the presence of fine structure.

The nuclide ^{206}Po

The mass number of this isotope was fairly well established from earlier investigations [22]. However, no isotope separated sample of ^{206}Po seems to have been studied hitherto. As mentioned above, the present authors utilized the alpha activity from this nuclide for the preliminary studies of the separation method. The alpha-particle energy spectrum obtained in one of the experiments is shown in Fig. 4. The intensity maximum was found at 5.22 MeV. The channel widths used in the measurements on this and the heavier isotopes studied have been much smaller than in the other cases. The reason was that the alpha-particle intensities have here been much higher than at the lower mass numbers. The manner of drawing the curve has thus been somewhat changed in order to simplify the diagram.

In a study of Rosenblum and Valadares [25], a fine structure component at 5.064 MeV was reported, which has not been found in later investigations [18, 19]. In some of our runs with ^{206}Po, an indication of an activity of this energy but probably with shorter half-life was actually seen, but, as it was not reproducible, it is likely to have

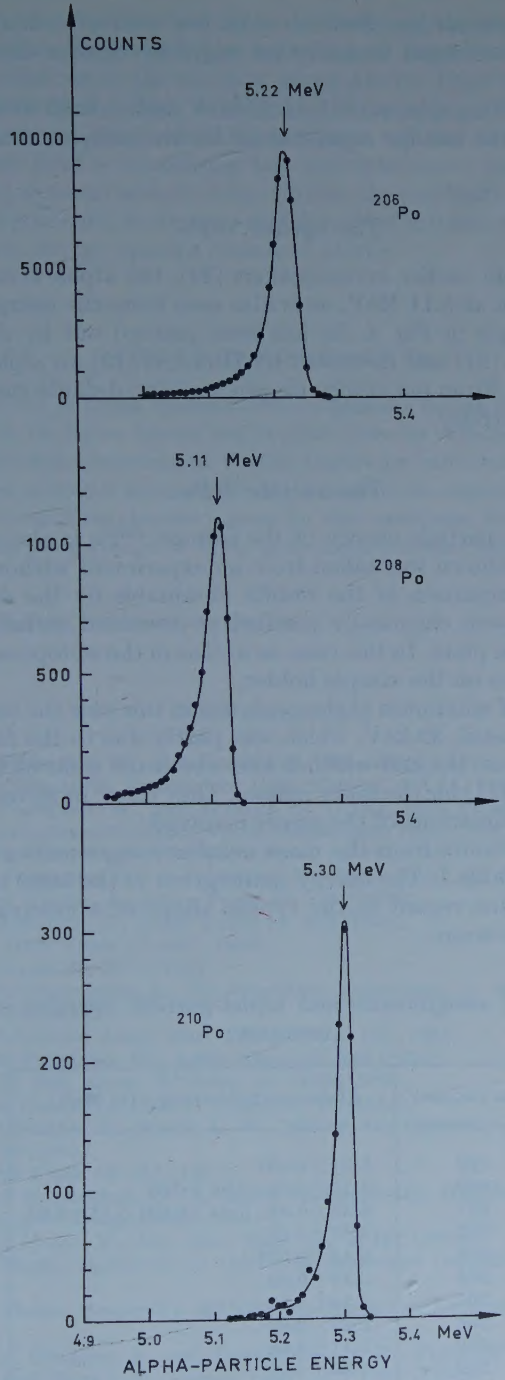

Fig. 4. Alpha-particle energy spectra from samples of ^{206}Po, ^{208}Po and ^{210}Po.

been due to some contamination. Because of its low intensity compared with that of the main activity, no attempts to study its origin by further chemical separations were made.

The full width at half maximum of the 5.22 MeV peak, about 40 keV, was the same for the samples from the isotope separator as for the samples obtained after simple evaporation.

The nuclide ^{208}Po

As was expected from earlier investigations [22], the alpha activity of ^{208}Po had the intensity maximum at 5.11 MeV, as is also seen from the energy spectrum of an isotope separated sample in Fig. 4. As has been pointed out by Asaro [26] and by Rosenblom and Tyrén [21] and discussed by Hummel [19] an alpha component has been seen at 4.74 MeV. From our study, we can make no definite statement about the existence of such an activity.

The nuclide ^{210}Po

The 5.30 MeV alpha-particle energy of the isotope ^{210}Po is also seen in Fig. 4. In this case, the diagram shown was taken from an experiment without isotope separation, which gave a comparison of the results obtainable by the different methods. The sample has here been chemically purified as described earlier and finally evaporated onto a platinum plate. In this case, as well as in the isotope-separated samples, no visible layer was seen on the sample holder.

The full width at half maximum of the peak was in this case the smallest obtainable with the ion chamber used, 30 keV, which was partly due to the fact that ^{210}Po is a pure alpha emitter. Thus, the half-width is here about the same as those obtained by Rosenblum and Tyrén [21] for the lower masses. They have, however, given their data in keV without any estimations of the errors involved.

A summary of our results from the mass number assignments of polonium alpha activities is shown in Table 1. The energy limits given in the table are based on standard deviations with due regard to the typical shape of a monoenergetic intensity peak in the energy spectrum.

Table 1. Mass number assignments and alpha-particle energies of light polonium isotopes.

Mass number	Alpha-particle energy (in MeV)
199	5.87 ± 0.03?
200	5.75 ± 0.03; 5.86 ± 0.03
201	5.57 ± 0.03; 5.67 ± 0.03; 5.77 ± 0.05
202	5.57 ± 0.03
203	5.48 ± 0.03?
204	5.39 ± 0.03
205	5.24 ± 0.05
206	5.22 ± 0.02
208	5.11 ± 0.02
210	5.30 ± 0.02

The degree of accuracy, which has been obtainable in the experiments reported in this paper is less than that which the authors had hoped to achieve. Some weaknesses are also pointed out in the account given above. Higher yields from the different procedures involved in this work and a more rapid detection technique are desirable. It is, however, likely that these wishes will be met. Our programme of development in this field is continuing but will take some time. For this reason it has been considered as unsuitable to delay further the publication of the work already done. In future experiments, however, more details of interest will certainly be found in the alpha-particle energy spectra discussed above.

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REFERENCES

1. Atterling, H., Forsling, W., and Åström, B., Proceedings of the International Conference on Nuclear Reactions, Amsterdam 1956. Physica *XXII*, 1193 (1956).
2. Atterling, H., Forsling, W., and Åström, B., ORNL-2606, Proceedings of the Conference on Reactions between Complex Nuclei, Gatlinburg, Tenn., U.S.A., May 5–7, 1958, p. 248.
3. Atterling, H., and Forsling, W., Arkiv Fysik *15*, 81 (1959).
4. Atterling, H., Forsling, W., and Åström, B., Arkiv Fysik *15*, 279 (1959).
5. Alväger, T., and Uhler, J., Arkiv Fysik *13*, 145 (1958).
6. Uhler, J., and Alväger, T., Arkiv Fysik *14*, 473 (1958).
7. Atterling, H., Arkiv Fysik *15*, 531 (1959).
8. Bjerge, T., Z. Physik *89*, 277 (1934).
9. Bleuler, E., and Goldsmith, J., Experimental Nucleonics, p. 42. Rinehart & Company, Inc., New York 1952.
10. Moyer, H. V., Polonium, Amer. Rep. TID-5221, p. 181, 1956.
11. Oelsner, G., and Forsling, W., Arkiv Kemi *11*, 349 (1957).
12. Bonét-Maury, P., Ann. phys., X^e Série, *XI*, 253 (1929).
13. Pate, B. D., and Yaffe, L., Can. J. Chem. *33*, 15 (1955).
14. Forsling, W., Alväger, T., Holm, L. W., Melin, O., Uhler, J., and Åström, B., Arkiv Fysik, *19*, 83 (1961).
15. Åström, B., Arkiv Fysik *12*, 215 (1957).
16. Perlman, I., and Rasmussen, J. O., Alpha Radioactivity, Handbuch der Physik, Vol. 42, p. 136. Springer Verlag, Berlin 1956.
17. Perlman, I., and Asaro, F., Ann. Rev. Nucl. Sci. *4*, 157 (1954).
18. Stoner, A. W., Thesis, University of California Radiation Laboratory Report UCRL-3471, 1956.
19. Hummel, J. P., Thesis, University of California Radiation Laboratory Report UCRL-3456, 1956.
20. Karraker, D. G., Ghiorso, A., and Templeton, D. H., Phys. Rev. *83*, 390 (1951).
21. Rosenblum, S., and Tyrén, H., Compt. rend. *239*, 1205 (1954).

22. Strominger, D., Hollander, J. M., and Seaborg, G. T., Table of Isotopes, Revs. Mod. Phys. *30*, 585 (1958).
23. Slätis, H., Hjalmar, E., and Carlsson, R., Arkiv Fysik *3*, 315 (1952).
24. Harris, R. G., private communication from W. E. Burcham.
25. Rosenblum, S., and Valadares, M., Compt. rend. *235*, 711 (1952).
26. Asaro, F., Thesis, University of California Radiation Laboratory Report UCRL–2180, 1954, p. 139.

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